REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(LEAVE BLANK)*

2. REPORT DATE
3 February 1995

3. REPORT TYPE AND DATES COVERED
Professional Paper

4. TITLE AND SUBTITLE
F-14 Flight Control Law Design, Verification, and Validation Using Computer Aided Engineering Tools

5. FUNDING NUMBERS

6. AUTHOR(S)
J. Renfrow, S. Liebler, J. Denham

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND 20670-5304

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The analog flight control computers (FCC's) in the F-14A/D airplane are currently being replaed with digital FCC's. This FCC upgrade will also include significant flight control law modifications which are designed to improve the aircraft's flying qualities throughout the operating envelope. Teamed with engineers from Grumman Aerospace, the NAWCAD was tasked as the lead activity in the total system development, integration, and testing of the new digital flight control system. These tasks included the development of improved control laws for both the up and away maneuvering flight envelope as well as the takeoff and landing configurations. These control laws engineering tools that were available on the main simulation computer system as well as desk top computer based systems. This paper specifically addresses the methods in use for the F-14 Digital Flight Control System (DFCS) program, however many of the methods used in this effort are currently being applied to the F-18E/F, V-22 and EA-6B programs

14. SUBJECT TERMS
DFCS, Flight Control Computers (FCC), F-14, SIMULINK

15. NUMBER OF PAGES
3

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

2/3/95

To: NAWC Security
From: W.H. Agnew, Head 4.3.2.6 NAVAIRSYSCOM Flight Controls Branch

Subj: F-14 TECHNICAL PAPER PUBLICATION AUTHORIZATION

I have read the technical paper "F-14 Flight Control Law Design, Verification, and Validation Using Computer Aided Engineering Tools", and it contains no classified information. I approved it for distribution to the general public.

W.H. Agnew
W. H. Agnew

Accesion For		
NTIS CRA&I		X
DTIC TAB		☐
Unannounced		☐
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

F-14 FLIGHT CONTROL LAW DESIGN, VERIFICATION, and VALIDATION USING COMPUTER AIDED ENGINEERING TOOLS

J. Renfrow, S. Liebler, J. Denham
Naval Air Warfare Center - Aircraft Division

1. ABSTRACT

The analog flight control computers (FCC's) in the F-14A/D airplane are currently being replaced with digital FCC's. This FCC upgrade will also include significant flight control law modifications which are designed to improve the aircraft's flying qualities throughout the operating envelope. Teamed with engineers from Grumman Aerospace, the Naval Air Warfare Center Aircraft Division (NAWCAD) was tasked as the lead activity in the total system development, integration, and testing of the new digital flight control system. These tasks included the development of improved control laws for both the up and away maneuvering flight envelope as well as the takeoff and landing configurations. These control laws were designed, verified, and validated using computer aided engineering tools that were available on the main simulation computer system as well as desk top computer based systems. This paper specifically addresses the methods in use for the F-14 Digital Flight Control System (DFCS) program, however many of the methods used in this effort are currently being applied to the F-18E/F, V-22 and EA-6B programs.

Incorporation of a control law design into the flight control computer's operational flight program requires the engineer to follow specific design and implementation tasks in order to prove the design. These design tasks include detailed control law development, open-loop feedback stability robustness tests, and closed-loop control law performance testing. The implementation tasks include coding the design into a full non-linear simulation, verification of the control law execution, validation of the control law performance, and certification to ensure the complete system is qualified for flight testing. Many of these tasks were accomplished using a full non-linear simulation of the F-14 combined with tools developed using the SIMULINK™ graphical analysis package. This paper will discuss the complete process from control law design to piloted evaluation while placing emphasis on the tools that were used to complete this effort.

2. INTRODUCTION

After many years of operational experience with the F-14A aircraft, several major deficiencies in the handling qualities have been identified in the high angle of attack flight regime as well as in the power approach configuration. In the high angle of attack flight regime, the most undesirable of these deficiencies are the transonic Mach (0.7 to 0.95) lateral-directional control induced departure characteristics. Maneuvering flight within these regions requires the pilot to avoid large lateral stick or rudder inputs since they may result in violent departures from controlled flight. If the departure inducing controls are held in long enough, the aircraft will progress towards a stabilized flat spin with angle of attack constant around 80-85 degrees, yaw rate of approximately 180 degrees per second, and pitch and roll rates essentially zero. Under these conditions, the pilot is experiencing positive six g's in the X-body axis direction (eyeballs out) and is virtually incapacitated. At lower Mach numbers and moderate angles of attack (20 to 30 degrees), a lightly damped lateral-directional oscillation (wing rock) degrades the pilot's ability to effectively perform air-to-air tracking tasks. In the power approach configuration (landing gear and flaps down), the F-14 generates significantly large adverse sideslip in response to lateral stick inputs. This adverse sideslip, coupled with the airplane's strong positive dihedral effect, tends to excite the Dutch-roll mode. This characteristic significantly degrades the pilot's ability to make accurate lateral line-up corrections during the terminal phases of a carrier approach. The pilot is constantly required to coordinate lateral stick inputs with rudder during the carrier approach phase, detracting from his overall situational awareness during this critical flight phase.

To fix the deficiencies involving the departure characteristics and wing-rock problem, NASA-Langley Research Center engineers designed and flight tested modifications to the analog control laws. The results of these tests are contained in references 1 through 3. Due to funding constraints, these control laws were never incorporated into the analog flight control system.

In order to improve documented deficiencies as well as obtain significant increases in flight control computer reliability and maintainability, the Naval Air Systems Command launched an aggressive program to secure funding to upgrade the F-14 analog flight control computers with state-of-the-art, all digital, flight control computers. The NAWCAD was tasked as the lead activity in the total system development, integration, and testing of the new digital flight control system. This digital flight control computer upgrade will allow the engineers to enhance the high angle of attack departure resistant control laws developed during previous flight test as well as completely redesign the power approach control laws to enhance the flying qualities during carrier approach and landings. This paper specifically addresses the design methods used to develop and conduct analysis on the improved control laws which are being incorporated into the F-14 DFCS.

Control Law Design Objectives

The Up and Away control laws will implement the NASA-Langley Research Center developed Automatic Rudder Interconnect control laws which were designed for the analog system during previous flight testing. There are some minor changes to these control laws which take advantage of the digital implementation of these control laws over their analog counterparts. These changes include improvements to the closed-loop stability margins over the entire flight envelope by using gain scheduling, and switching logic which is designed to allow for smooth transitions between the various operating modes of the control laws.

The Power Approach control law design was a completely new architecture which capitalizes on the latest methods which have been demonstrated on more modern aircraft applications. The control law design team focused on maximizing the flying qualities improvements that could be realized given the constraint of the F-14's limited authority control system. With this limited authority system, the actuator duty cycle is far lower than that of modern, full authority, fly by wire control systems. This limitation resulted in design tradeoffs in order to minimize actuator activity to the greatest extent practicable.

Control Law Design Methodology

In order to support the design and development cycle of an aircraft flight control system, it is important to develop a process combined with a set of design tools which enable the

control law designer to prototype, implement, analyze, and test a candidate design in a short time period (see Figure 1).

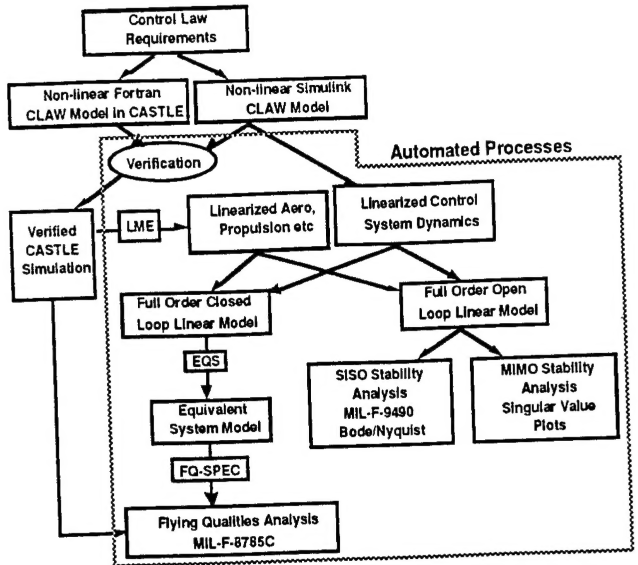

Figure 1
Flight Control Law Design Process

This process must be automated as much as possible, since the iterative control law design will be subject to numerous changes during the development cycle of the airplane. These control law updates can be patched into the digital flight control computers overnight and testing can resume the next day on the new design. Due to this quick turnaround capability, the control law engineer must have an automated design tool in which the changes can be evaluated from a system stability, performance, and safety of flight aspect.

This design process is embedded around the non-linear simulation of the vehicle, making it desirable to formulate a set of tools which interface with the main simulation executive and can manipulate the simulation models in order to extract and store needed information such as linear models and non-linear time histories. The first process is the ability to trim the non-linear simulation at an equilibrium condition and extract linear models of the vehicle subsystems such as aerodynamics, propulsion, actuator, and sensor systems using the Linear Model Extraction (LME) tool. These linear models are then combined to form both open and closed-loop linear models in which the control analysis process can begin. The open-loop analysis is accomplished to ensure that the system meets the stability requirements outlined in the MIL-F-9490 flight control system specification. The closed-loop analysis requirements are dictated in the military specification MIL-F-8785C, "Flying Qualities of Piloted Airplanes". This specification uses a fourth order representation of the closed-loop dynamic response characteristics of the airplane to specify the required vehicle handling characteristics. Since many of the closed-loop linear representations of airplanes are well over 100th order models, these models must be reduced to an equivalent fourth order model for specification compliance testing. This model reduction must be accomplished without a significant loss in model fidelity. This process is accomplished with the EQuivalent System (EQS) toolbox. Once these fourth order models have been obtained from the EQS toolbox as well as non-linear time history data from the Controls Analysis and Simulation Test Loop Environment (CASTLE) simulation, they are down-loaded into the Flying Qualities Specification (FQ-SPEC) toolbox which automatically compares the closed-loop models to applicable specifications and generates a report detailing which requirements were met (or not met). This paper focuses on the design process outlined in Figure 1.

CASTLE Architecture

The primary mission of the Manned Flight Simulator (MFS) facility at the NAWCAD is to provide high fidelity simulation support capabilities for all Naval aircraft. The support provided includes high risk flight test support, engineering support for flight control system development, avionics testing, accident investigations, pilot familiarization, and emergency training. To support the wide variety of aircraft types and simulation tasks, engineers from the MFS developed an innovative approach using a standard simulation architecture to meet these diverse requirements. The resulting CASTLE executive architecture was developed to meet these needs. This architecture delineates models which are generic among all aircraft from those models which are aircraft specific. These generic models include items like the rigid body equations of motion, atmospheric modeling, landing environments (shipboard and land-based), laboratory communications, etc. The CASTLE architecture also provides a user-friendly environment to execute the simulations.

3. CONTROL LAW DESIGN AND ANALYSIS TECHNIQUES

Once all of the linear models of the aircraft's subsystems have been successfully obtained, the designer can begin the control law design process. The F-14 power approach control system is referred to as the PA ARI (Power Approach Automatic Rudder Interconnect). The design for the PA ARI control laws was formulated and implemented in a SIMULINK™ model. Table I provides an overview of the aircraft handling qualities deficiencies and the control loops used to correct them.

Problem	Solution
Lightly damped Dutch-roll	Estimated beta-dot to rudder
Large adverse sideslip	Latstick to rudder feed-forward
Low roll damping	Roll rate command tracking
Non-linear roll response	Modified latstick to spoiler
Unstable spiral mode	Yaw rate to diff stab

Table I Deficiency Corrections

The feedback gains were determined using standard MATLAB tools for performing classical linear control system design such as root-locus and discrete system frequency response. Since this control design will be employed in a digital computer, the feedback gain design was conducted using discrete time models which included all known high frequency dynamics. Tustin's method was used for the discrete filters since this is what will be implemented in the flight hardware. For gain selection analyses, an open-loop model is required with the loop breaks at the feedback gain locations.

Once feedback gain computations are complete, the closed-loop linear model is computed. The closed-loop response to various pilot inputs is then checked. To ensure the open-loop design objectives were met, the final closed-loop system eigenvalues are then computed.

Open-loop Analysis

After all the feedback gains have been selected, the single-input single-output (SISO) and multi-input multi-output (MIMO) stability robustness properties of the system must be analyzed at the sensor feedbacks and actuator commands to ensure the required system performance specifications are met.

The frequency response of each of these loops is computed with the other loops closed to ensure the SISO robustness specifications (MIL-F-9490) are met.

SISO robustness analysis is a necessary step in any control system design. However, when the system is multivariable, SISO methods cannot necessarily guarantee stability of the closed-loop system if parameter variations

occur simultaneously in more than one feedback path. In order to gain additional confidence in the SISO design, MIMO analysis is conducted to determine the effect of uncertainty occurring in all loops simultaneously. The two most common uncertainty formulations are the additive and multiplicative uncertainties.

As yet no requirements exist for MIMO stability margins. However, for the frequency range considered in this case, the least conservative MIMO margins actually pass the SISO robustness criteria of MIL-F-9490 (6 db GM, 45 deg PM). The closed-loop system is not nominally stable, since the yaw rate to differential stabilizer feedback path was intentionally designed to place the spiral mode at the origin of the s-plane. As expected, the MIMO stability margins become arbitrarily small for frequencies approaching zero rad/sec.

Autopilot Sample Rate Determination

In order to minimize the computational throughput requirements, the various autopilot outer loops were evaluated during a trade study to determine if the calculation rate of these loops could be reduced from the nominal 50 Hertz update rate without a significant loss in performance. The goal was to use flight conditions from varying parts of the flight envelope to ensure that any changes made would be valid throughout the envelope. The effect of sampling was minimal at or above 25 Hz, but loss of phase and gain margins was seen for the 10 Hz case. On further study at other flight conditions, 25 Hz was chosen as the sampling rate for all autopilot loops.

Closed-loop Analysis Methods

The final step of the F-14 control law design/analysis process is evaluation of the closed-loop system. This can be accomplished by piloted evaluations of the real-time simulation, batch mode simulation analysis, and equivalent system model analysis. The current fixed-wing military flying qualities specification MIL-F-8785C defines aircraft handling characteristics in terms of its equivalent system model characteristics such as Dutch-roll frequency/damping as well as direct transient response specifications such as time to 30 degree bank angle for full lateral stick input. In order to efficiently analyze these characteristics for modern state-of-the-art aircraft such as the V-22, F-18, and F-14 DFCS, a need was identified to integrate this analysis process within the non-linear simulation architecture.

In the late 1980's NAWCAD and Systems Control Technology (SCT) developed a set of software tools for computing equivalent system models called EQS, reference 4, and performing flying qualities analysis called SCT-SPEC, reference 5. In the last several years, NAWCAD engineers have re-designed these tools and implemented them as MATLAB toolboxes called EQS and FQ-SPEC. These tools take advantage of the latest advances in robust model order reduction and interactive graphics capabilities.

The primary motivation for computing equivalent system models is that direct extraction of equivalent rigid body response modes such as the short-period or Dutch-roll from the high-order linear model of a complex flight control/airframe combination can often lead to incorrect conclusions about the aircraft flying qualities. This is especially true when the flight control system contains dynamics in the same frequency range as the closed-loop rigid body modes. What is required is an equivalent model of the overall system dynamics that approximates the combined flight control/airframe system. A modal analysis of this equivalent model then yields the parameters required for military flying qualities specification compliance analysis. Several methods are available for determining equivalent system models including i) maximum likelihood parameter identification, ii) matching frequency response data and iii) model order reduction of a high order linear model. Method 3 is used by EQS. Advantages of the model order reduction approach is that it is a self-starting, non-iterative procedure. The order of the reduced model can be arbitrarily set, giving the analyst much insight into the effective order of the system. The EQS process consists of 5 steps including i) direct truncation of unconnected modes, ii) singular perturbation reduction (removes high frequency modes), iii) modal truncation (removes less prevalent modes), iv) balanced model reduction (removes less prevalênt modes) and v) computation of equivalent time delay.

The FQ-SPEC Toolbox addresses the need to efficiently analyze flying qualities of a complex airframe/flight control system throughout the flight envelope. FQ-SPEC analyzes flying qualities by comparing the aircraft model characteristics against requirements in the military flying qualities specifications such as MIL-F-8785C, MIL-F-83300 and the proposed NADC-82146-60. The data used by FQ-SPEC to analyze flying qualities comes from the following sources: i) the equivalent system model produced by EQS, ii) the high order model input to EQS and iii) non-linear simulation time histories.

The equivalent system models are used to test modal characteristics such as short-period frequency and damping. High order linear models are used to generate time responses for specification requirements involving transient response parameters such as roll attitude to sideslip angle ratios. High order linear models are also used to generate the frequency responses to test compliance of specifications involving response bandwidth. Non-linear simulation time history data is used to determine compliance with specifications involving large amplitude control inputs, such as time to achieve 30 deg roll attitude using full lateral control input.

4. SUMMARY

The design process for a set of flight control laws is an intensive and complex task to ensure that adequate flying qualities exist over the entire operating envelope of the aircraft as well as maintaining safety of flight considerations. The principle resource to the control design engineer is the non-linear simulation of the flight vehicle. During the development phases of an air vehicle, data are continuously collected and incorporated into the non-linear simulation as new data become available. This requires the control designer to re-evaluate the control laws in order to optimize the gains and possibly the structure to ensure the original design requirements remain satisfied. This is a monumental task for complex aircraft systems, therefore, it is of paramount importance that an integrated and automated approach to this problem be implemented. Due to the numerous aircraft types that NAWCAD engineers must analyze, an automated approach is of utmost importance. To meet these challenging needs, the engineers at the MFS have devised this automated control design and analysis approach which is completely integrated into all of its aircraft simulations. The result is a set of tools that allow the engineer to quickly respond with detailed analysis for changes in the non-linear simulation, problems discovered during flight testing, incident investigations, and life cycle production support to the fleet.

5. REFERENCES

1. NAVAIRTESTCEN Report of Test Results, SA-3R-80, Lewis, Hildreth;"Navy Evaluation of a NASA Developed Automatic Rudder Interconnect for the F-14A Airplane", 1980.
2. NASA Technical Memorandum, Nguyen, Gilbert, Gera, Iliff, Enevoldson; "Application of High-a Control System Concepts to a Variable Sweep Fighter Airplane"; Aug 1980.
3. NAVAIRTESTCEN Report of Test Results, SA-57R-80, Hildreth, Lewis; "Navy Evaluation of a NASA Developed Automatic Rudder Interconnect for the F-14A Airplane", 1980.
4. Anderson, M.R., "V-22 Simulation and Flight Control System Analysis, Equivalent System Analysis (EQS) - User's Guide", SCT Report No. 6016-162-1, April 1990.
5. Rabin, U.H., "SCT-SPEC Version 3.0, Flying Qualities Analysis Program for MIL-F-8785C, MIL-F-83300, and NADC-82146, User's Guide and Implementation Guide", SCT Report No. 6116-200-1, May 1990.